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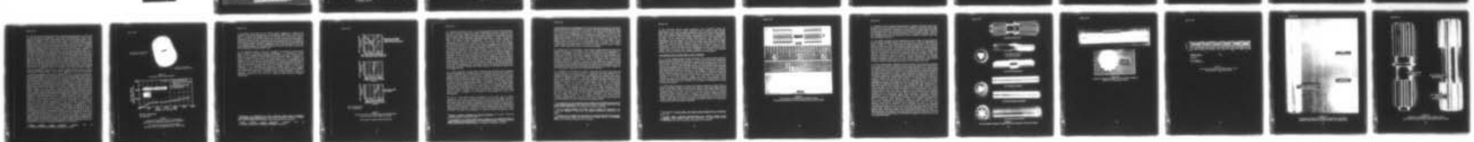

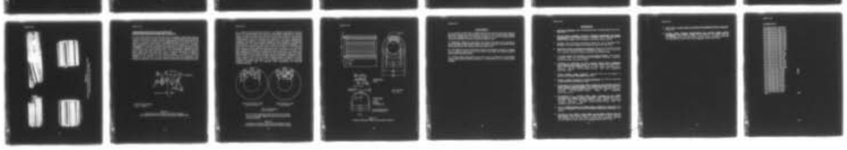

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Technical Memorandum

AIRCRAFT ENGINE DRIVEN ACCESSORY SHAFT COUPLING IMPROVEMENTS USING HIGH-STRENGTH, LOW WEAR POLYIMIDE PLASTIC

Mr. Aleck Loker
Project Engineer

Systems Engineering Test Directorate

30 December 1976

NAVAL AIR TEST CENTER
PATUXENT RIVER, MARYLAND

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Splined shaft couplings which connect generators, pumps, starters, and other accessories to aircraft engines and gearboxes frequently exhibit high wear and failure rates. In an effort to improve aircraft safety, reliability, and readiness, the Naval Air Test Center has engaged in a continuing spline improvement program over the past 9 years. This Technical Memorandum describes the development and test of two unique spline coupling modifications which have proven to be essentially immune to wear and failure in the aircraft power transmission applications which have been evaluated. Specific design information and application concepts are discussed to introduce this new spline coupling technology to mechanical equipment designers.

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PREFACE

Engine driven accessories, such as generators, starters, and pumps, are commonly connected to their respective power takeoff shafts by spline couplings. These shaft couplings which allow rapid installation and removal of the accessory are capable of high torque transmission and are considered to be self-centering. However, splined shaft couplings are subject to rapid wear in many aircraft applications and frequently are the object of expensive and time-consuming maintenance and overhaul action. The Naval Air Test Center has engaged in a continuing spline coupling improvement program during the past 9 years. In the process, new spline technology has been developed which affords mechanical equipment designers a practical solution to the shaft coupling problem. Various Work Unit Assignments executed during this program are identified by references 6, 9, 10, 12, and 14. These references also identify the specific reports giving the details of each of the spline improvement programs. This Technical Memorandum is intended to condense the results of the last 9 years into a presentation of two basic spline design modifications which can be used to extend the operating life of aircraft mechanical equipment shaft couplings.

The first of these basic spline design modifications has been assigned U.S. Patent Number 3,620,043 of November 16, 1971 to ARINC Research Corporation with royalty-free rights to the Department of Defense. The second spline design modification patent application has been filed by the Naval Air Test Center and assigned Navy Case Number 61068.

The leadership and assistance of Dr. Allen R. Matthews in these efforts is greatfully acknowledged.

APPROVED FOR RELEASE

J. G. WISSLER
ACTING COMMANDER, NAVAL AIR TEST CENTER

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INTRODUCTION

1. The information presented herein is a brief history of the development of two basic spline couplings which offer practical solutions to the problem of spline shaft coupling wear. This Technical Memorandum describes, in general terms, the processes that cause wear and failure in conventional involute splines, and relates the apparent success of the two recently developed spline coupling improvements to this background.

BACKGROUND

2. Before describing the new coupling design, a brief review of existing spline technology is in order. The spline coupling technique is very old--perhaps 500 years. During the years, various spline forms have been developed to accomplish the basic intention of transmitting torque through a coupling which may slide freely along its axial direction. The spline, which evolved from the practice of locking shafts and hubs together (see figure 1) with keys and keyways, can be thought of as a shaft having multiple, loose fitting keys.[1] The splines in most conventional designs are parallel to and are formed integrally with the shaft. They mate with corresponding grooves cut into a hub or fitting. The most innovative approach until recently has been the use of involute (curved) rather than straight sided keys or teeth. Such involute splines result in greater torque carrying ability and exhibit a self-centering action. The presently accepted standards utilizing involute tooth profiles evolved from the gear industry. However, unlike gears, splines theoretically exhibit no relative motion between mating teeth. Additional refinements have been in the areas of surface finishes, lubricating coatings, and additional curvature (crowning) of the tooth profiles. In theory, the additional refinements would not be necessary if it were not for the phenomenon of rapid wear exhibited by many spline couplings in service, most notably in the aircraft and automotive industry.

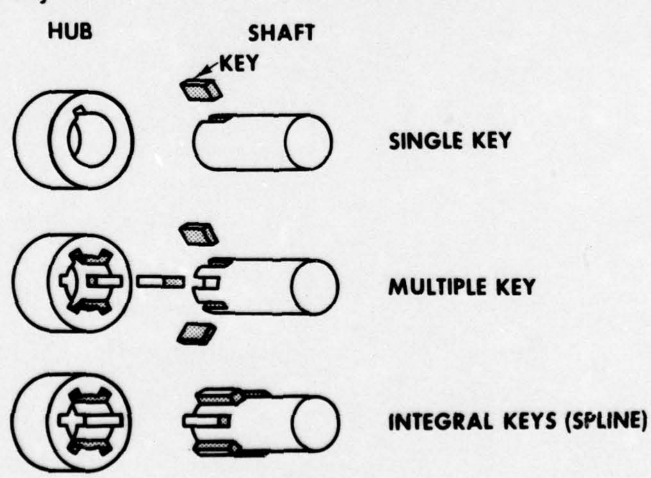


Figure 1
Evolution of Spline Coupling Method from Key and Keyway

[1] Machinery's Handbook, 1962, The Industrial Press, 93 Worth Street, New York, New York.

3. This wear problem is the area of major concern. Extensive research into the problems of spline wear through theoretical studies and through experimental analysis has shown that the spline couplings wear and subsequently fail due to fretting, abrasion, spalling, and corrosion.[2] The last two processes may be minimized by proper spline material and lubricant selection, but fretting and abrasion are not so easily dismissed. With perfect alignment of the mating parts, the involute shape of the teeth will ensure that no sliding motion will take place between the teeth, and assuming spalling is controlled by minimizing tooth loading, then wear will not occur. However, in the real world, alignment is never perfect. If the two parts of the spline coupling are not concentric or if the rotational axes are not parallel, then misalignment exists and this causes a rocking or sliding motion between the loaded surfaces. The motion between the two surfaces, which are held together at high contact pressure due to torsion, produces fretting and wear.

4. Fretting, according to one popular theory, occurs when pressure between two solid surfaces is concentrated on a small number of high points in both surfaces, causing plastic flow and cold welding. These welded points are subsequently fractured as slip between the surfaces takes place; the process liberates particles which are the remnants of the fractured cold welds.[3] These abrasive particles may then oxidize into even harder, more abrasive material. The formation of the fretting particles tends to accelerate the wear process if they are retained in the coupling due to the presence of a grease "lubricant." Splines in service in the aircraft industry exhibit varying durations of service, depending on the degree of misalignment control, vibration which increases misalignment, and on the frequency of relubrication and cleaning. If the couplings are cleaned frequently, and the best lubricants are used and replenished, the spline couplings exhibit significantly less wear. Laboratory studies of misaligned grease lubricated splines[4] imply that cleaning and relubrication should be done at least every 50 hours and ideally every 25 hours of operation for maximum spline life (see figure 2). The ultimate in this approach is the so called "wet pad" in which the spline interface is continuously or intermittently flushed by an oil lubricant. This lubrication replenishment washes away the abrasive products of fretting which would accelerate the surface wear if left in the spline coupling. However, wet pad features add to the spline coupling problems of seals and other complexities associated with forced lubrication systems. A simpler, more practical solution to the spline wear problem would be welcomed by all mechanical equipment designers.

[2] Aircraft Spline Reliability Predictive Technique Development and Design Methodology, Second Progress Report, 1 February 1975 to 30 June 1975 by Dimitri B. Kececioglu, et.al., University of Arizona, Tuscon, Arizona.

[3] Fretting, SAE Aeronautical Information Report No. 47, 15 December 1956, Society of Automotive Engineers Incorporated, New York, New York.

[4] Spline Wear Effects of Design and Lubrication, Paper No. 74-DET-84 October 1974, for the American Society of Mechanical Engineers by P. M. Ku and M. L. Valtierra, Southwest Research Institute, San Antonio, Texas.

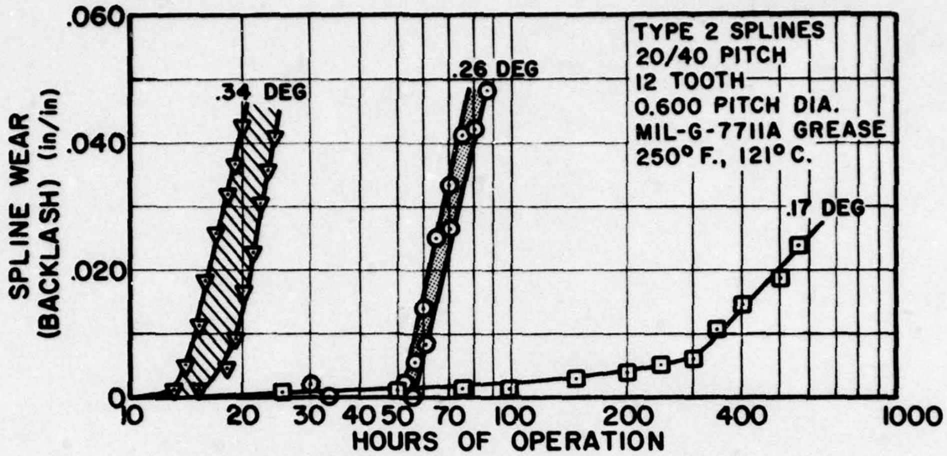


Figure 2
Standard Grease Lubricated Involute Spline
Accelerated Wear Due to Angular Misalignment

(350 in.-lb (39.5 N-m) applied torque at 4400 RPM)

5. Service experience with spline couplings has demonstrated the lack of control of misalignment, lubrication, and cleaning necessary to ensure prolonged coupling life. To put this problem in perspective, a recent Navy sponsored study[5] over an 8 year period indicated that 40 percent of the fixed wing and 70 percent of the rotary wing aircraft were affected by the spline wear problem. To take a closer look, the same study found that the single engine A-4 aircraft has 174 spline connections excluding those within accessories. Larger multiengine aircraft contain even more spline couplings. Obviously, low reliability due to wear in such a frequently used component is a major factor in aircraft reliability or operational readiness. Inaccessibility of these couplings makes maintenance difficult and time-consuming. Consequently, the degree of maintenance demanded by spline wear is inconsistent with the operational philosophy of military aircraft.

PURPOSE

6. The succeeding paragraphs describe the development of a basic modification of the spline coupling design which incorporates an expendable or sacrificial element. The sacrificial element is allowed to wear (at a very moderate rate), preventing wear of both the mechanical accessory drive shaft and the mating engine or gearbox power takeoff shaft. The modified spline coupling design incorporating a sacrificial element has been utilized in two basic variations by the Naval Air Test Center. Each type is described separately in the following paragraphs.

[5] A Critical Survey and Analysis of Aircraft Spline Failures, Final Report, 18 August 1971, by M. L. Valtierra, R. D. Brown, P. M. Ku, Southwest Research Institute, San Antonio, Texas.

7. The two new spline couplings have proven through laboratory and fleet service to be essentially immune to the processes of fretting, corrosion, abrasion, and wear. In addition to their proven life, these new couplings require no lubrication or cleaning during service. They have so far been designed as accessory interface couplings to connect equipment, such as generators, constant speed drive (CSD) power transmissions, and pumps to engine driven gearboxes. These equipment can be categorized as continuous operation, moderate to heavy loads at high rotational speeds, and are responsible for the majority of spline reliability problems. Other splines, such as are used within engines or gearboxes, although heavily loaded, receive intermittent or continuous lubrication and consequently provide more acceptable service life. Other splines which generally exhibit acceptable performance are the low to moderately loaded, intermittently operated actuator splines which are usually grease lubricated.

MS14169(AS) CIRCULAR SPLINE COUPLING

8. The first coupling, referred to as an MS14169(AS) circular (rather than involute) spline, is illustrated in figure 3. The circular spline coupling was designed for the Navy by the ARINC Research Corporation, Annapolis, Maryland. Three notable differences between the circular and involute spline partially account for the performance of the new coupling: the circular cross-section of each tooth provides a more uniform surface loading, thereby reducing tooth stresses, the crowned spline accommodates more angular misalignment before tooth jamming, and most importantly, the process of fretting is virtually eliminated as metal to metal contact is not present. It should be pointed out that involute splines may be modified to accommodate increased misalignment by shortening the spline (lower length to diameter ratios) and by crowning. On one Navy application (F-4 CSD), tooth jamming occurred at 26 minutes angular misalignment using a standard involute spline. When this spline was modified to include crowning, jamming did not occur until 60 minutes angular misalignment.[6] However, although tooth jamming is forestalled with crowned involute splines, fretting induced wear is not mitigated since slippage still occurs between the metal spline coupling surfaces.

[6] Evaluation of Sundstrand 30 KVA Constant Speed Drive Redesigned "Self-Aligning" Input Spline Shafts; Final Report, Report No. ST-46R-71, 9 March 1971 by R. P. Gallant, Naval Air Test Center, Patuxent River, Maryland.

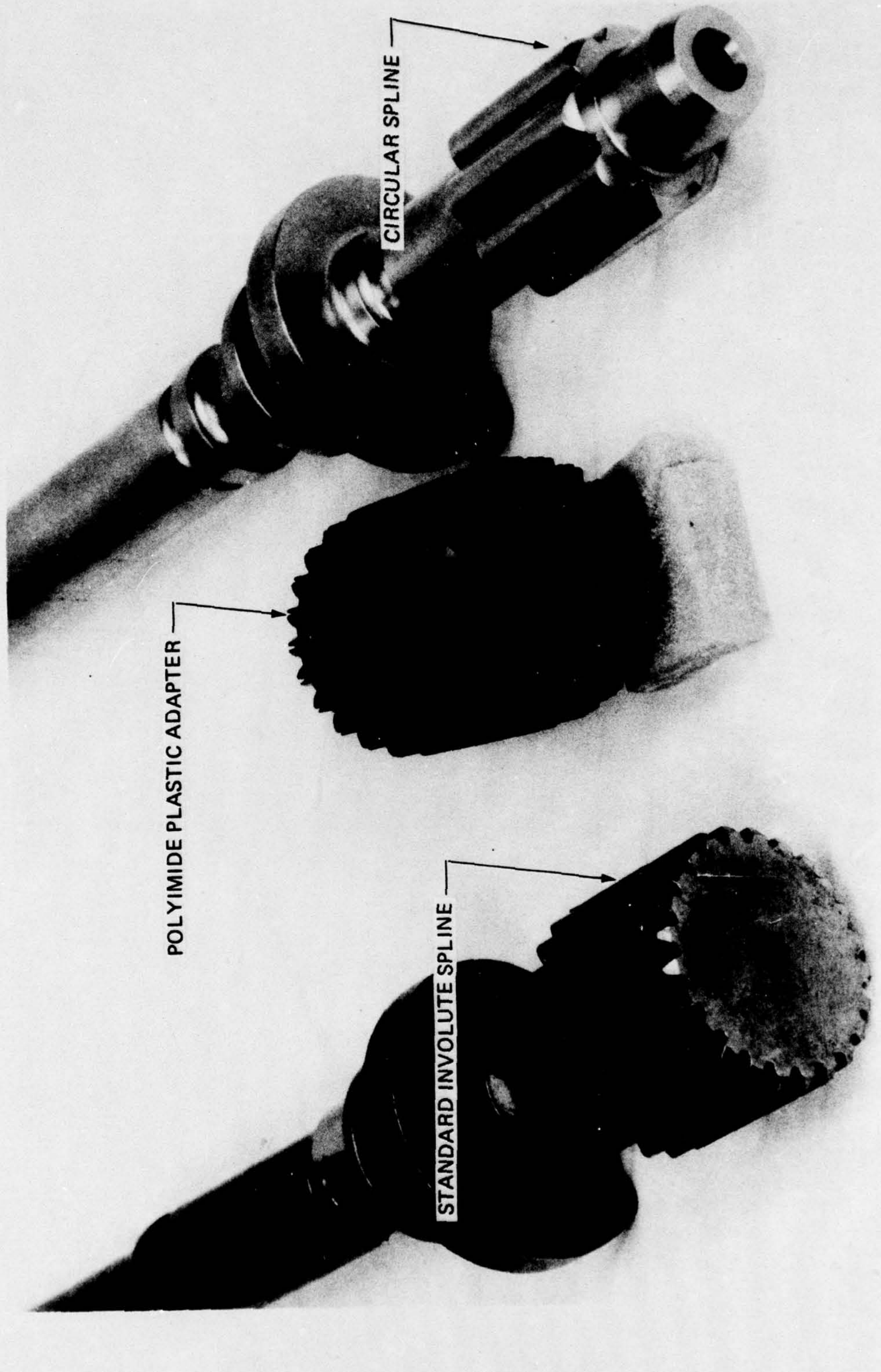
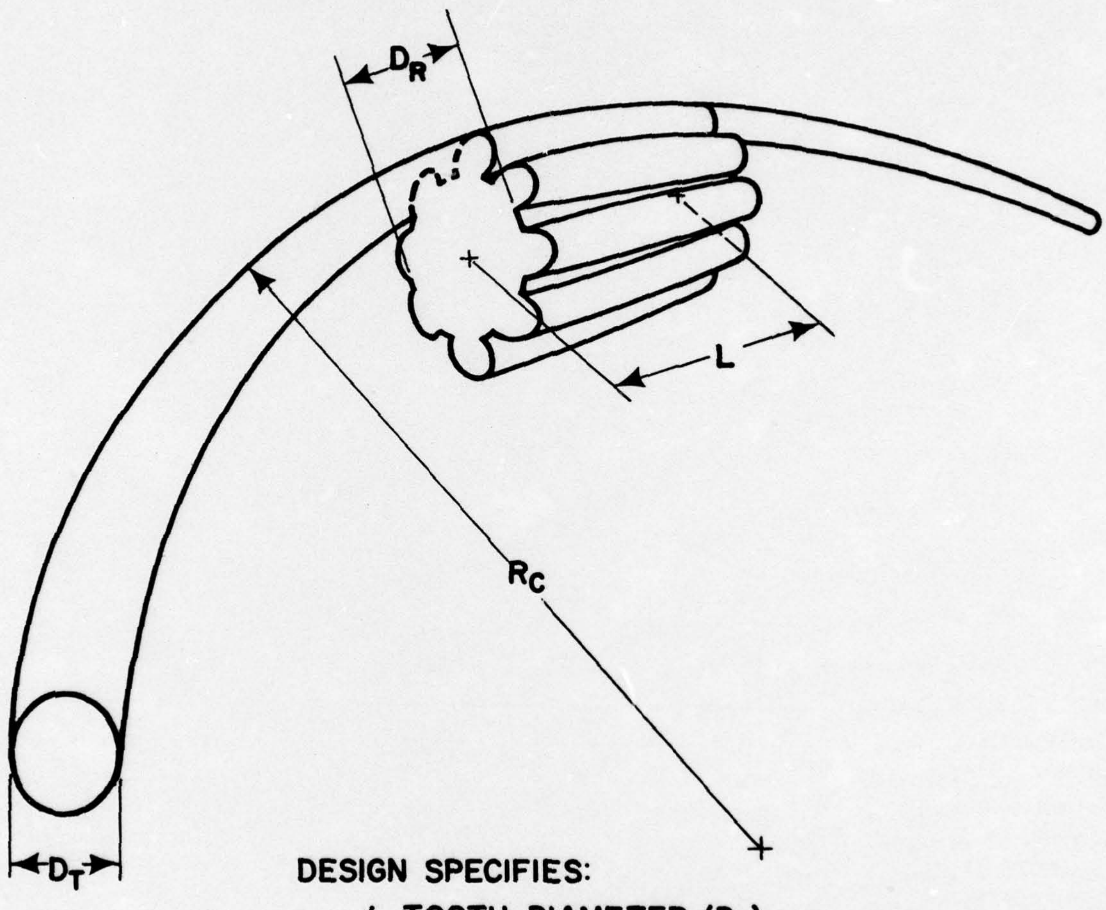


Figure 3
Comparison of the Circular Spline with a Standard Involute Spline (EC-130 aircraft test samples)

9. In the circular spline, the teeth are segments of a torus of circular cross-section (see figure 4). The radius of the torus or the spline crown may be varied to accommodate the intrinsic misalignment present in the coupling installation. The greater the crown curvature (i.e., the smaller the crown radius) the greater the misalignment before the onset of tooth jamming. The greater the tooth width and number of teeth, the lower the tooth contact pressure. Stress concentrations can also be minimized by judicious selection of spline tooth curvature.



DESIGN SPECIFIES:

1. TOOTH DIAMETER (D_T)
2. SPLINE LENGTH (L)
3. ROOT DIAMETER (D_R)
4. CROWN RADIUS (R_C)
5. NUMBER OF TEETH (N)
6. MAX. SPLINE O.D. (D_O)

Figure 4
Generation of the Circular Spline Tooth Form from a Torus

10. This new spline would probably offer no significant improvement in service life if it were not for the second half of this unique coupling design, a muff or spline adapter (see figure 5) which accommodates the new circular spline shape on the inside and conforms to the standard involute shape on the outside. Muffs or spline adapters have been used in the past in an attempt to provide more misalignment tolerance, but since they were produced from metallic materials subject to fretting and had the typical involute tooth profiles, they have not proven to be a significant advantage (although they have proven to be beneficial). Frequent attention to cleaning and relubrication is still required. The new circular spline design uses a nonmetallic muff which fits tightly into the mating spline rather than loosely as in the case of the metallic spline adapter. This is an extremely important point which can make the difference between design success and failure. The nonmetallic adapter is vulnerable to hoop stresses which are generated by spline wind-up under high torque loads. The hoop stresses lead to tensile failure of the plastic unless offset by a compressive preload obtained through an interference fit in the female spline. The fit between the adapter and the accessory drive shaft is a loose fit so that the ease of installation of the accessory is not affected by this coupling modification. The material which has undergone laboratory and flight testing is Dupont's VESPEL ® isotropic SP-1, a high strength (30,000 psi (20.7×10^7 Pa) compression) polyimide plastic. This material is produced in rod stock and exhibits an excellent machining characteristic. VESPEL ® SP-1 may also be molded into various finished shapes by a direct forming process using a powder base; however, the resulting product does not possess the isotropic characteristic which aids in predicting the degree of success to be expected from its use.[7] Testing of adapters made by the direct forming process has been insufficient at this time to determine their acceptability. Other plastics are also under laboratory and flight evaluation at this time. For optimum life, the nonmetallic muff is designed to require a press fit (approximately 100 pounds (445 N)) in the engine accessary gearbox output shaft. Being a plastic part, the adapter's internal circular spline configuration very quickly conforms to the shape of the circular splined accessory shaft with minimal wear. A slight dusting has been observed during the brief running-in period of these couplings as the coupling conforms to the misalignment present in the installation. Because the adapter material is able to deform plastically without fracture to conform to the crowned circular tooth profile, tooth loads or pressures are distributed more evenly over the inner surfaces of the adapter. On a microscopic level, the minute surface irregularities in the metal shaft produce similar deformation in the plastic adapter and are suspected to be responsible for the release of the material referred to as dusting through a ploughing action. It is doubtful, however, that contact pressures are high enough or if the plastic material properties are conducive to the phenomenon of cold weld formation which is instrumental in fretting. Consequently, the short period of running-in is followed by an exceptionally long period of service life devoid of any significant wear. Tests have indicated that the presence of a lubricant has little effect on the material properties and actually assists the wear-in process by reducing frictional wear. Figure 6 shows the increase in backlash of a typical design driving a 6,000 RPM, 30 KVA generator for 1,100 hours at approximately two-thirds load while mounted on a laboratory test stand at an angular misalignment of 20 minutes.

[7] DuPont VESPEL Design Handbook, Copyright 1970 by E. I. duPont de Neumours & Company, Wilmington, Delaware.

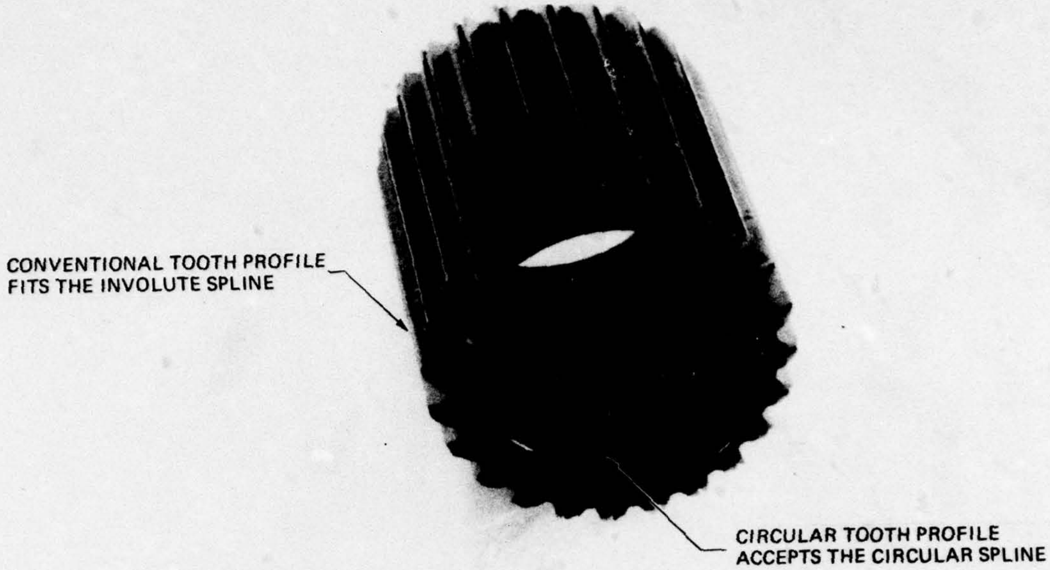
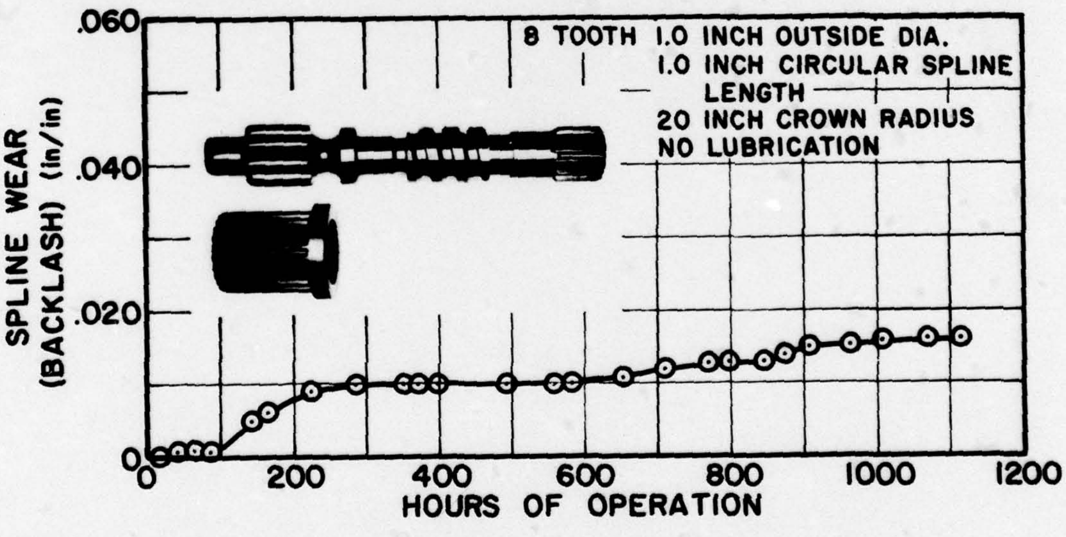


Figure 5
Polyimide Plastic Spline Adapter



METRIC CONVERSION
1 in = 25.4 mm

Figure 6
Laboratory Endurance Test of Circular Spline
Operated at an Angular Misalignment of 20 Minutes

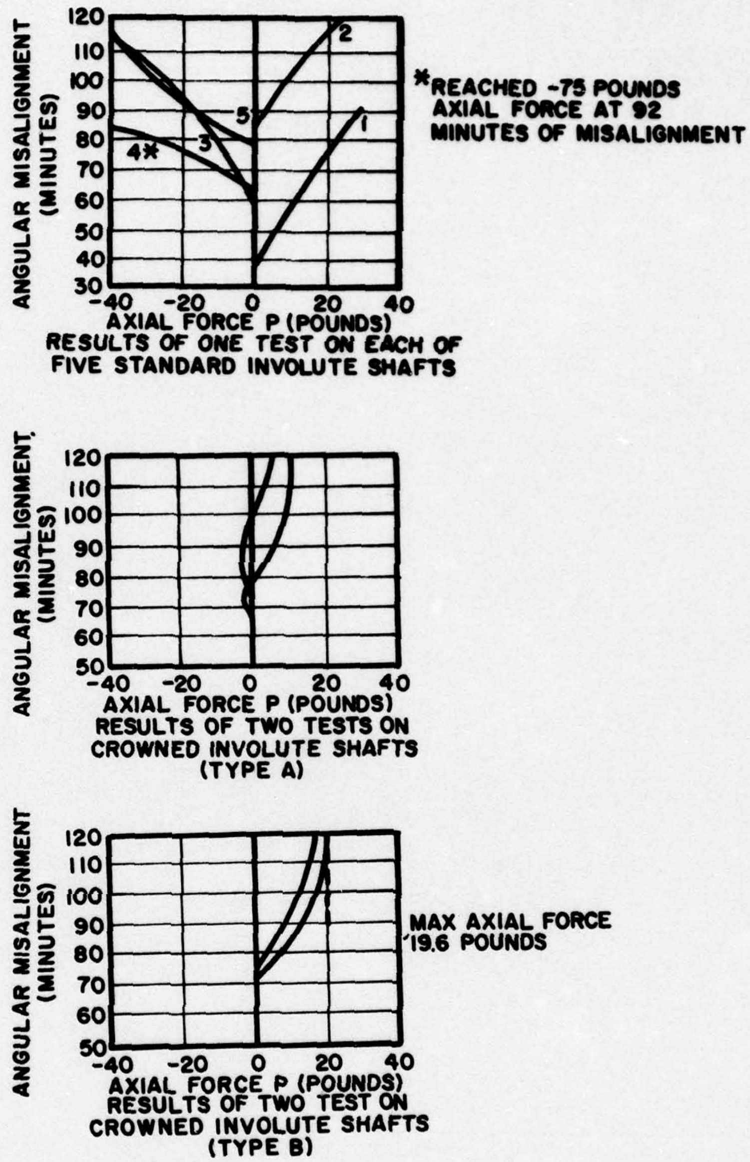
(F-4 aircraft constant speed drive shaft)
(360 in.-lb. (40.7 N-m) applied torque at 6000 RPM)

11. In effect, the success of the circular spline coupling is a result of the realization that spline misalignment and consequent surface slip is inevitable. In order to minimize the harmful effects of such slip, the tooth load or contact pressure per unit area has been reduced and a plastic material (the expendable or sacrificial element) has been interposed between the driving and driven components of the spline coupling. The plastic material then deforms and accommodates the tooth jamming due to excessive misalignment while redistributing the tooth load more evenly throughout the coupling. Rapid wear does not take place because the basic mechanism of fretting cannot occur.

12. An additional benefit of this new coupling is the reduction in axial forces which normally accompany excessive misalignment. In conventional involute splines, tooth jamming during misalignment produces excessive localized tooth loads, but also produces an axial thrust along the shaft. Figure 7 illustrates a typical example of axial forces in involute splines due to misalignment and jamming. It can be seen that crowning delays the occurrence of jamming and thus results in lower axial forces.[6] This axial thrust is not only damaging to the shaft, it also is very injurious to the bearings of both the driving and driven machinery. It is suspected to be responsible for premature bearing failures in the driven accessories. Due to the accommodating feature of the plastic muff or adapter, tooth jamming does not result in excessive local contact pressures. The material also has a low coefficient of friction.[7] Both of these properties result in a significant reduction in the axial force produced during severely misaligned installations.

[6] Evaluation of Sundstrand 30 KVA Constant Speed Drive Redesigned "Self-Aligning" Input Spline Shafts; Final Report, Report No. ST-46R-71, 9 March 1971 by R. P. Gallant, Naval Air Test Center, Patuxent River, Maryland.

[7] DuPont VESPEL Design Handbook, Copyright 1970 by E. I. duPont de Neumours & Company, Wilmington, Delaware.



METRIC CONVERSION
1 lb = 4.45 NEWTON

Figure 7
Axial Forces Due to Misalignment and the Reduction of Axial Forces Due to Spline Crowning

(F-4 aircraft constant speed drive shaft)

13. Attempts have been made to coat involute splines with low friction plastic materials to minimize spline wear. Various materials and surface treatments have been used with some limited beneficial results.[8] However, the geometry of the involute spline makes significant improvements difficult to attain. The standard spline tooth loads are essentially distributed along lines of contact between the teeth, and during extreme misalignment, the actual contact pressure is concentrated on very small portions of each tooth. When this occurs, plastic coatings (and lubricants) are ejected from between engaging teeth in the coupling due to cold flow. The thin coating is thus quickly exuded from the portions of the coupling under extreme load, and wear progresses from that point as if no coating were present. Similarly, tooth binding results in the excessive axial thrust previously discussed. The circular spline coupling requires no special cleaning or lubrication during service, but precautions to prevent contamination might be considered. Just as the standard involute splines are subject to wear by abrasive particles, the circular spline coupling could wear if sufficient abrasive material were introduced into the space between the metal splined shaft and the plastic spline adapter. However, it is expected that the effect of abrasive contaminants would be minimized by the ability of the plastic to deform. The abrasive particles would thus be compressed into the plastic surface. No special precautions have been taken to prevent coupling contamination during the thousands of failure free hours logged thus far.

14. To date, prototype circular spline couplings using polyimide plastic adapters have been designed for and flight tested on the Navy's A-4, F-4, P-3, and EC-130 aircraft. These test splines are all interface couplings (seemingly the most severe application) connecting the constant speed drive (CSD) to the engine accessory gearbox (AGB), the electrical generator to the CSD, or the generator to the AGB. A total of 20,138 hours has been logged on 20 splines on the three types of interfaces with no coupling failures and no measurable wear. The highest flight time on an individual shaft thus far is 1,832 hours on a P-3 generator drive shaft. The procedure of changing from the involute spline to the circular spline requires minimal aircraft down time since only the removable accessory (CSD, generator, etc.) drive shaft is changed. The spline adapter which is inserted in the mating gearbox spline is designed to be installed in worn splines as well as new installations.

15. The F-4 CSD input spline is illustrative of the worst type of service experience. The CSD was originally driven by the aircraft engine accessory gearbox through standard grease lubricated involute splines which often wore to a knife edge in less than 100 hours. Misalignment on some installations was so severe that the resultant tooth jamming produced axial forces of sufficient magnitude to cause the CSD input shaft to withdraw from the engine gearbox (as if the thermal disconnect were actuated). Axial forces as great as 200 pounds (890 N) have been recorded.[9] The spline was redesigned to a crowned involute configuration which

[8] Design of Spline Couplings for Fretting Mitigation by P. M. Ku, Southwest Research Institute, San Antonio, Texas.

[9] Development of a Circular Spline Shaft Coupling for the 30AGD03 CSD/J-79 Engine Transfer Gearbox Interface, Final Engineering Report, December 1973 by R. Coss and H. Brown, ARINC Research Corporation, Annapolis, Maryland.

temporarily prevented disengagement by forestalling tooth jamming, but rapid wear quickly reduced the crowning effect resulting in jamming and disengagement. When the crowned involute spline was combined with a wet pad lubrication system, spline wear and ultimate disengagement were postponed to slightly over 500 hours. The incorporation of a circular spline and a polyimide plastic adapter has led to a shaft design which produces an axial force of less than 17 pounds (67.9 N), and after 679 flight hours (without wet pad lubrication) shows no evidence of spline wear or adapter failure. During the F-4 circular spline tests, one CSD initiated (over temperature) spline disconnect was accomplished with no damage to the adapter circular spline or gearbox spline. This CSD was placed back in service without repair or parts replacement of the circular spline coupling.

16. During the P-3 test program, circular spline equipped generators have been installed in gearboxes with severely worn female splines with no degradation or evidence of changes in wear rates. The plastic adapters have been designed to fit snugly in new or badly worn female couplings. One gearbox output shaft spline was so severely worn that depot level overhaul to replace the shaft was in order. However, installation of the plastic adapter by squadron level maintenance personnel restored the aircraft to service and this engine has accumulated 488 hours since that time. Adapters and generator shafts have been swapped or mixed and matched with no adverse effects. Rapid acceleration and deceleration rates are encountered routinely by these couplings during engine start and feather sequences. No circular spline component wear or degradation is evident.

17. In addition to the flight test programs, laboratory tests have been conducted by the Navy and by two contractors. Over 1,800 hours have been obtained on one coupling running at 20 minutes angular misalignment with minimal wear and no evidence of impending failure.[10] One hundred applications and removals of shock loads were imposed on the P-3 generator coupling (including twenty-five 300 percent load cycles) with no evident degradation of the plastic circular spline adapter.[11] Typical A-4 metallic involute splines were run in a laboratory misalignment set-up and found to exhibit tooth jamming at 40 minutes angular misalignment. The couplings were then filled with a high temperature silicone grease and run at 35 minutes misalignment angle for 17 hours. Fretting corrosion and heavy wear were evident upon examination. A prototype circular spline was then run for 255 hours at the 35 minute angle (unlubricated) with no wear evident and only slight deformation of the plastic component. All other operating conditions (torque, speed, etc.) were identical to the involute spline tests.[12] Coupling compatibility with various aircraft fluids, lubricants, and solvents has been determined by a series of immersion and materials tests.

[10] Development of a Circular Spline Shaft Coupling for the 28B95 Generator/T-56 Engine Gearbox Interface, Final Engineering Report, December 1973, by R. Coss and H. Brown, ARINC Research Corporation, Annapolis, Maryland.

[11] Test on VESPEL Bushing with ARINC Shaft on 28B95 A.C. Generator, Test Report No. E302385, 17 June 1974, The Bendix Corporation, Eatontown, New Jersey.

[12] Evaluation of the ARINC Circular Spline for the Bendix 28B139 Generator Input Shaft, Final Report, Report No. WST-17R-75, 17 March 1975 by J. T. Meredith, Naval Air Test Center, Patuxent River, Maryland.

18. The following primary design parameters were considered during the development of the circular spline: operating torque, number of teeth, circular spline tooth radius, torque transmitting diameter, and crown radius. Present designs which have completed flight testing have been optimized to achieve a desired per unit area load for an estimated angular misalignment. This was accomplished by providing a crown radius which permits safe operation under both load and misalignment since the plastic from which the adapters are made exhibits fatigue properties in the same manner as metals. The circular spline design for the 0.800, 1.200, and 1.625 inch (20.32, 30.48, 41.28 mm) pitch diameter sizes has been standardized[13] after selecting the best parameters to achieve maximum torque transmitting ability at the worst level of misalignment normally encountered by the engine driven accessory drive shafts. Reference 14 presents the detailed calculations which preceded this standardized family of circular splines.

FIVE-EIGHTHS INCH EXPENDABLE SHAFT COUPLING

19. A second coupling design taking advantage of the high-strength polyimide plastics has been developed by the Naval Air Test Center based on information obtained while testing the circular spline couplings. This coupling, 5/8 inch (16 mm) size, which is used on small hydraulic pumps, emergency generators, and some starters, must transmit relatively high intermittent or oscillating, fatigue inducing torque. The polyimide plastic exhibits a fatigue susceptibility as do most commonly used high-strength materials. Because of this fatigue consideration, a different spline design was used for the 5/8 inch (16 mm) coupling to maximize the bearing surface or load carrying area of the plastic element. The circular tooth design and crowning were therefore discarded in favor of a tooth shape that is more easily adapted to the small diameter coupling and offers the maximum torque transmitting surface area.This design has been found to be similarly immune to the process of fretting and wear and tolerant of the degree of misalignment normally encountered in service.

20. Initial designs attempted to transmit the required torque via a plastic and steel replica of the steel "dogbone" shaft pictured in figure 8. This initial design suffered from several errors: failure to account for the inner steel shaft windup and the resultant plastic hoop stress which led to tensile fracture; failure to properly preload the plastic external spline to produce the necessary compressive stress previously found to be important to the coupling success; use of a steel inner shaft having a triangular cross-section which does not provide sufficient contact area or proper contact angle to efficiently transpose the applied torque into compressive versus shear stress in the plastic component.

[13] MS14169(AS), Circular Spline and Adapter Details, Engine Driven Accessories, 6 May 1976.

[14] Circular Spline Coupling Standardization for Aircraft Engine Driven Accessories, Final Report, Report No. SY-47R-76, 10 March 1976 by Mr. J. T. Meredith, Naval Air Test Center, Patuxent River, Maryland.

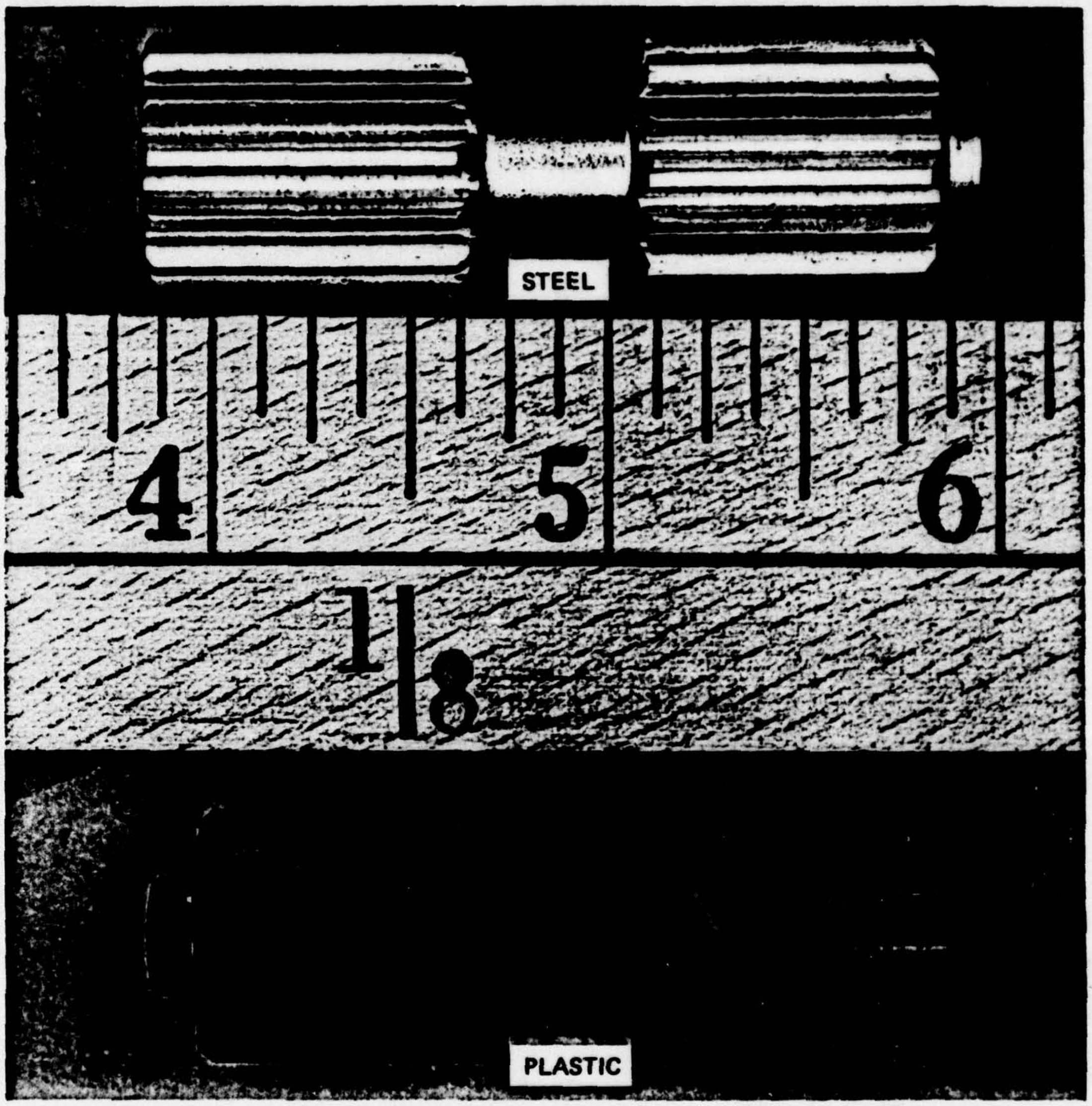


Figure 8
Comparison of Standard Steel "Dogbone" Pump
Drive Shaft and Plastic and Steel Replacement (Initial Design)

21. Through a series of design changes depicted in figure 9, the initial errors were eliminated and a successful 5/8 inch (16 mm) coupling was achieved. Each design iteration was evaluated by comparing the results of static torque applications with the preceding static torque test results until a design was produced which transmits the maximum torque with minimal deformation of the plastic element. The two best configurations were then subjected to cyclic loading to evaluate their wear rate and fatigue sensitivity.

22. The optimum triangular shaft configuration shown in figure 10 was installed in a H-53 primary hydraulic system pump and subjected to full load applications as shown in figure 11. This coupling had previously demonstrated a 50 foot-pound (68 N-m) static torque limit. The coupling undergoing fatigue tests failed after 186 full load cycles (3.1 hours). The failure analysis concluded that excessive slipping motion between the plastic element and the inner steel shaft due to windup under load and the repetitive strain cycles caused heating of the plastic element and sufficient reduction in the plastic compressive and shear strength to allow the amount of deformation shown in figure 12. This discoloration of the steel shaft provides permanent evidence of the heat buildup. Consequently, this coupling design is considered useful only for very low cyclical torque (5 foot-pounds (7 N-m) or less) or constant torque applications (below 50 foot-pounds (68 N-m)).

23. The six toothed shaft configuration shown in figure 13 was similarly evaluated in the same H-53 primary hydraulic system pump and subjected to repeated full load applications. The coupling had previously demonstrated a static torque rating of 125 foot-pounds (170 N-m) based on the level at which the steel shaft sheared (see figure 14). It should be noted that in this configuration the weakest element is the steel shaft and that no cracks or other evidence of overload were observed in the plastic component. This coupling endured 3,085 full load application cycles over a 51.4 hour period with minimal plastic element wear and no signs of heating or imminent failure. This success was followed by an additional test of the same components of 300 hours duration with the coupling interface intentionally misaligned 20 minutes (0.33 degree) and with full load application cycles of 1 hour. Following the additional 300 hour test, the coupling was again disassembled to inspect for signs of wear, heating, or imminent failure. A minor amount of wear was evident from a trace of plastic dust which had accumulated in the roots of the internal splines. This wear was so slight as to be immeasurable. The plastic component fit the inner steel shaft as tightly after 350 hours as when originally installed. The six toothed inner shaft bore no evidence of heating as had been experienced in the triangular shaped shaft. The shaft temperature, checked immediately after the test, was 38°C. Hydraulic fluid temperature was limited to 37°C to minimize pump degradation during the coupling endurance test. Microscopic examination of the plastic elements revealed no cracks which, if present, would indicate impending failure. Similarly, no cracks or wear were observed in the steel inner shaft or outer steel splines. This set of test conditions was duplicated during a second 350 hour test of the same steel shaft with two new plastic inserts. During this second test, the driving component was an actual H-53 gearbox shaft which was severely worn and had been rejected by the Naval Air Rework Facility. The results of the second 350 hour test were identical to the first test, indicating that this design can successfully be applied to severely worn as well as new gearbox splines.

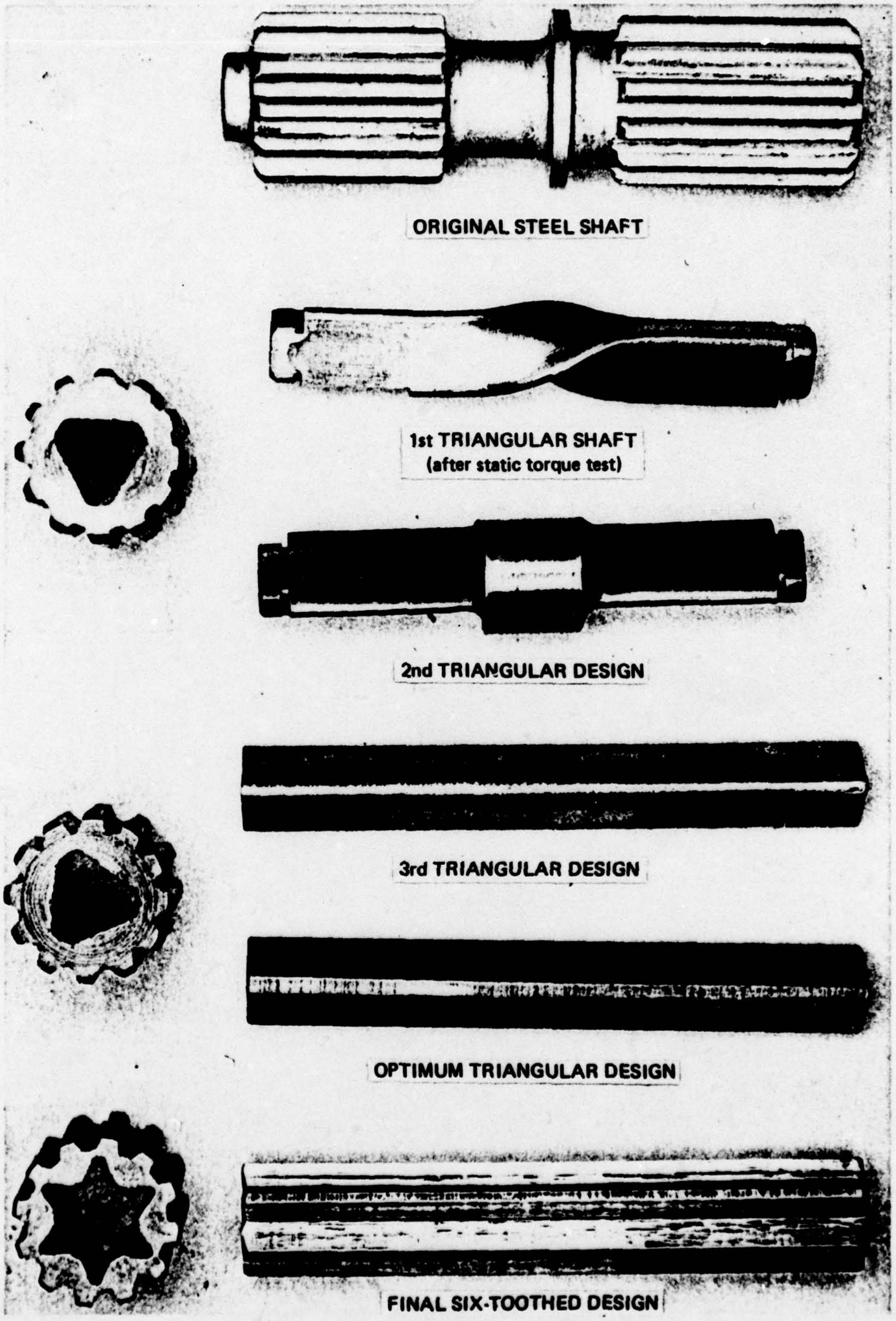
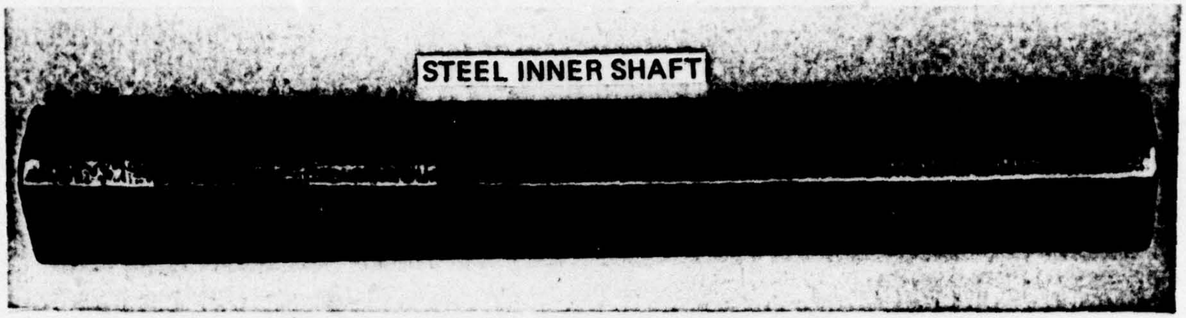


Figure 9
Various Design Changes in Plastic and Steel "Dogbone" Pump Drive Shaft



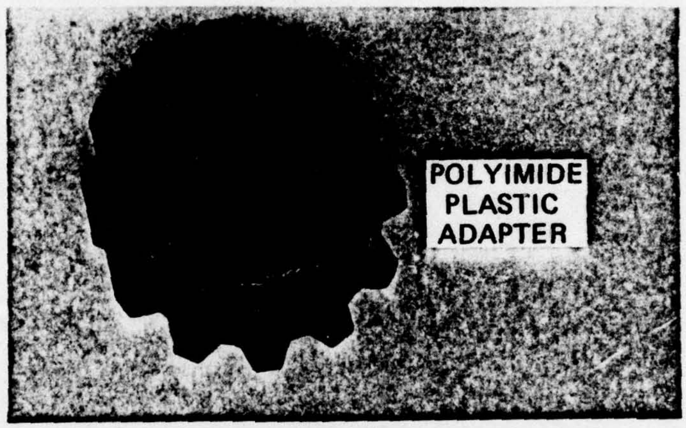


Figure 10
Optimum Triangular Design Plastic and Steel "Dogbone" Shaft for H-53 Hydraulic Pumps

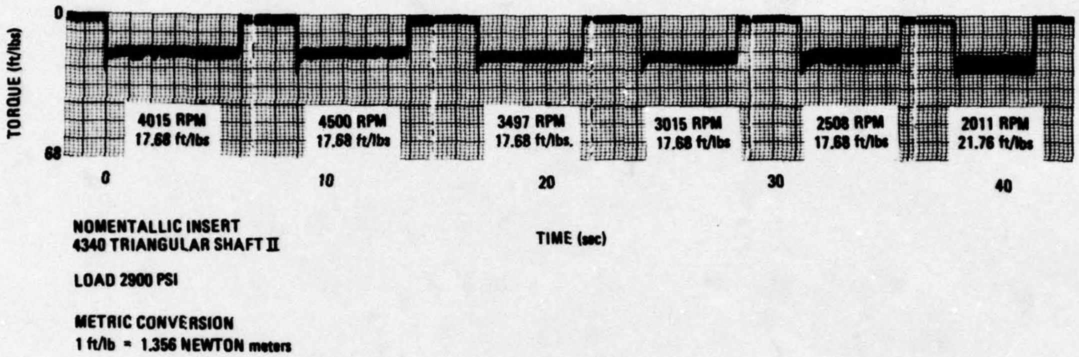


Figure 11
Recording of Torsional Load Applications to the H-53 Hydraulic Pump Drive Shaft

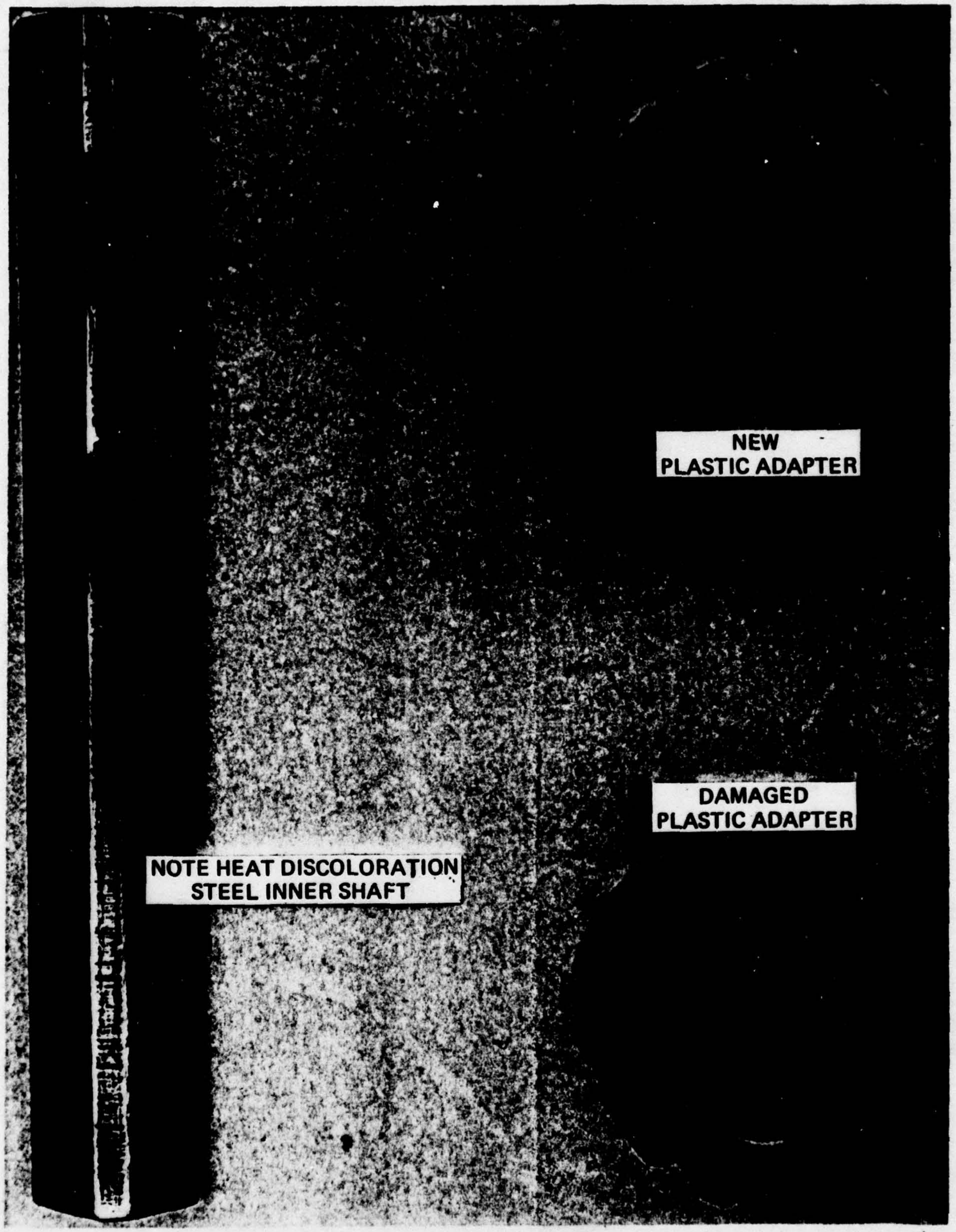


Figure 12
Comparison of Optimum Triangular Design Steel and Plastic "Dogbone" Shaft Before and After 186 Full Load Applications

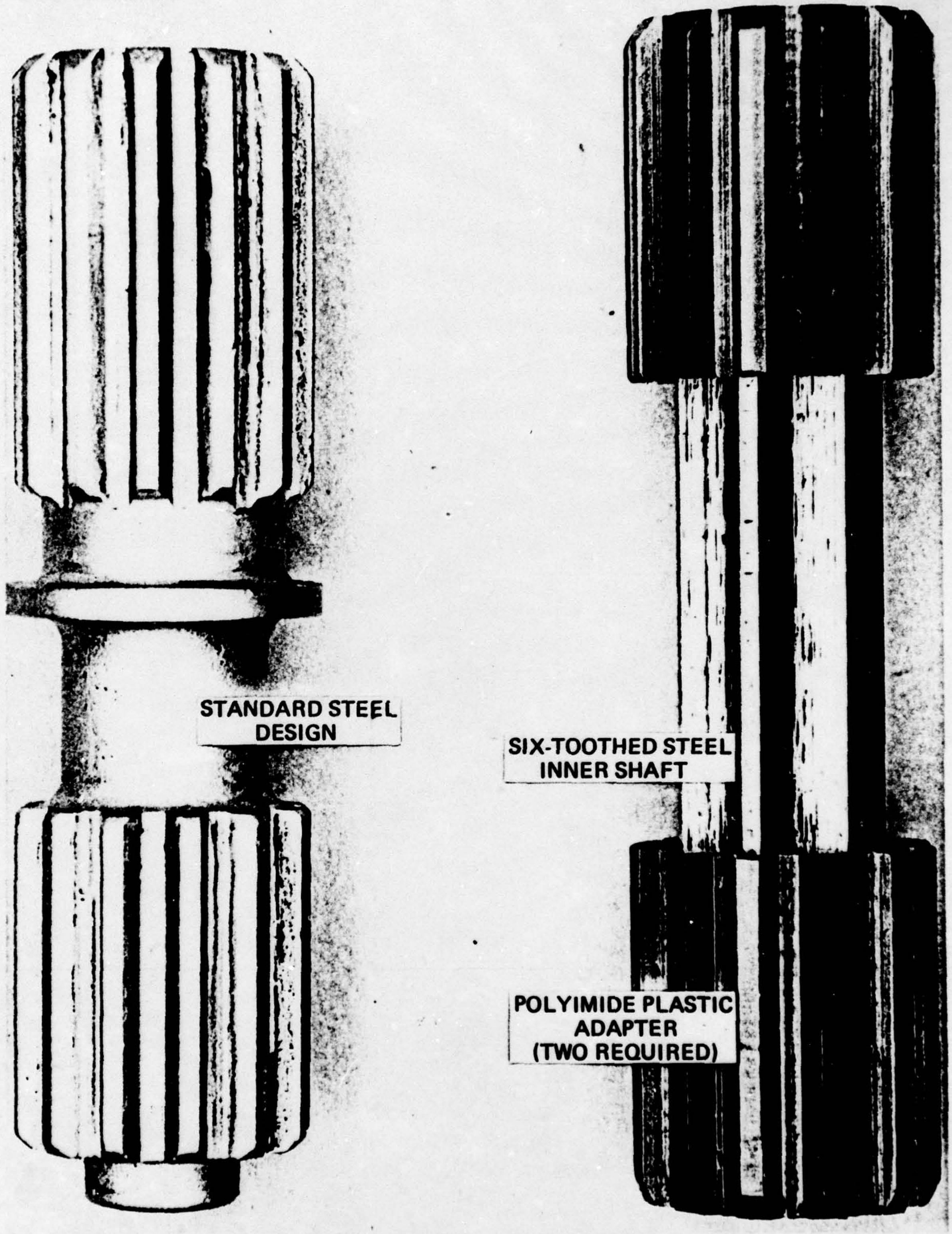


Figure 13
Comparison of Standard Steel "Dogbone" Shaft
with Final Six-Toothed Steel and Polyimide Plastic Design

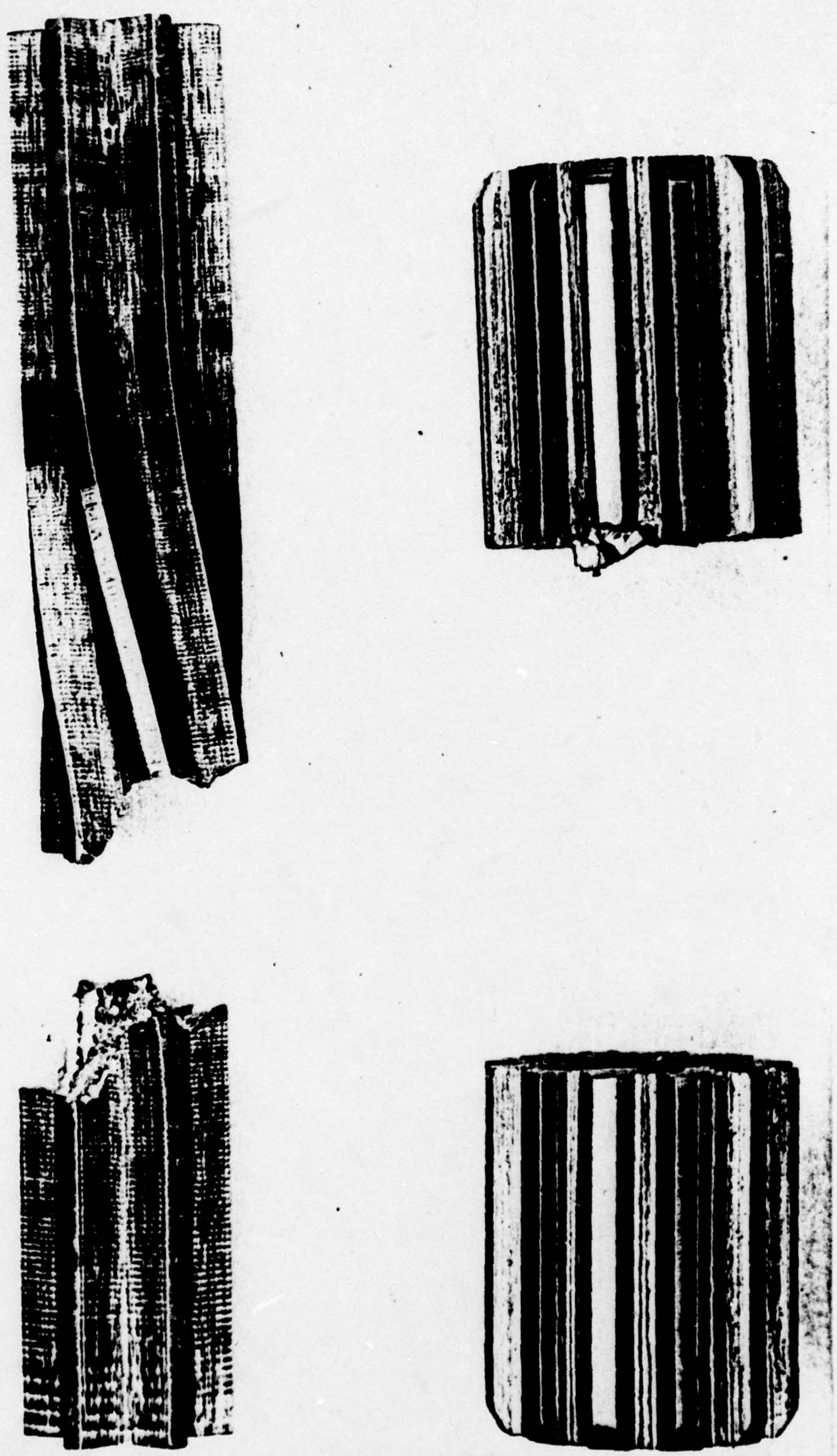
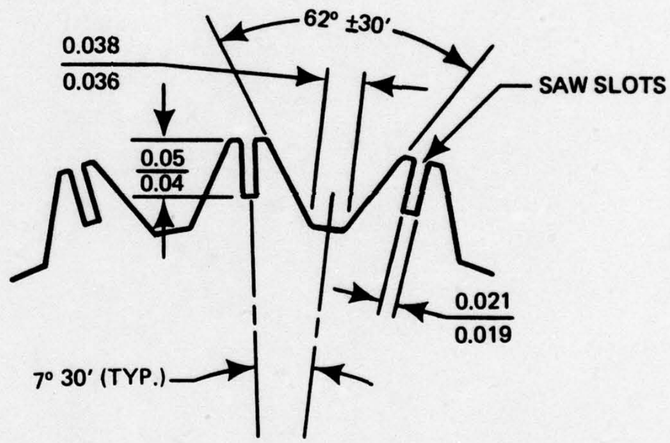


Figure 14
Results of 125 Foot-Pound (170 N-m) Static Torque
Test Showing Sheared Steel Inner Shaft

COMPARISON OF THE CIRCULAR SPLINE AND THE FIVE-EIGHTHS INCH EXPENDABLE COUPLINGS

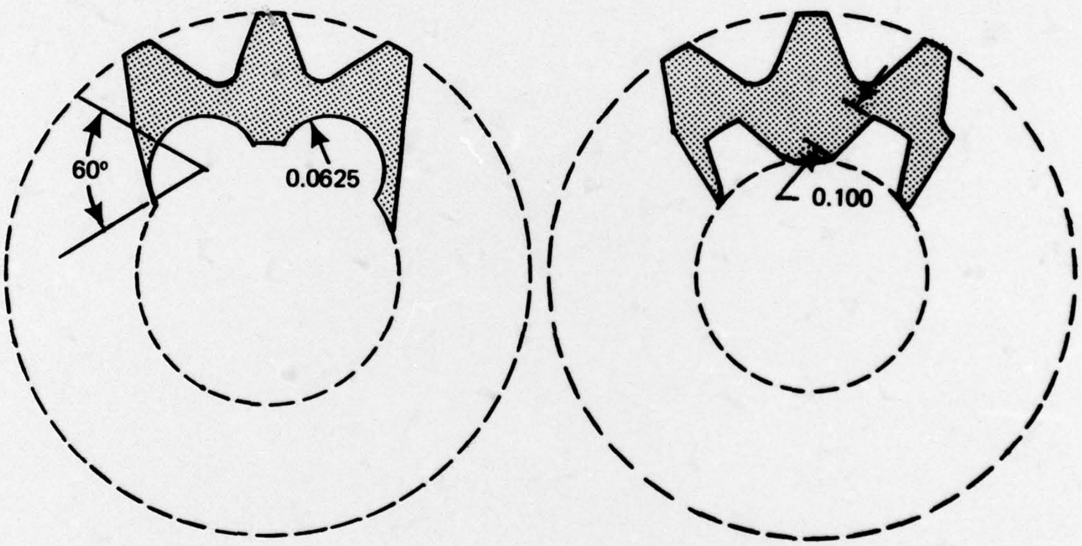
24. The circular spline and the 5/8 inch (16 mm) coupling as previously noted are similar in their use of a plastic element which is installed tightly into the splined cavities of the driven accessory and the engine/gearbox power takeoff shaft. The tight fit is necessary to provide the compressive preload to overcome the tensile stress generated by shaft windup under load and the binding due to excessive misalignment. To achieve some degree of uniformity in fit when the plastic insert is installed in worn or new splined cavities, the circular spline coupling uses 0.020 inch (0.5 mm) saw slots (see figure 15) in the intentionally oversized external plastic spline teeth. This allows the teeth to contract as necessary to tightly fit their mating part. In the 5/8 inch (16 mm) coupling, the teeth are similarly designed to be oversized but the 0.020 inch (0.5 mm) saw slots have been eliminated. This was done to reduce manufacturing costs, and preliminary tests indicate an adequate fit is achieved in both new and severely worn splined cavities.



METRIC CONVERSION
1 inch = 25.4 mm

Figure 15
Illustration of the Circular Spline Plastic Adapter
Showing the 0.020 Inch Saw Slots as Required by MS14169(AS)

25. A second obvious difference between the two designs is the shape of the inner shafts. The circular spline teeth have been described as segments of a circular torus of constant cross-section, whereas the six teeth of the 5/8 inch (16 mm) coupling are flat sided and the shaft is not crowned. The benefits of crowning and circular profile teeth are considered less important in the small coupling when compared with necessity of achieving maximum torque transmission and minimum machining costs. The circular spline couplings have been designed to minimize the stress imposed on the plastic element due to spline jamming when misaligned. The small 5/8 inch (16 mm) coupling achieves success by reliance on the favorable contact angle (pressure angle) and large contact area (see figure 16) as well as the high compressive strength of the polyimide plastic material. The success of the small coupling points to possible reductions in the manufacturing cost of the larger (0.800 through 1.625 inch (20.32 through 41.28 mm)) couplings by elimination of the saw slots and use of flat sided or involute shaped teeth without crowning. In other words, scaling up the 5/8 inch (16 mm) coupling design or design of a plastic involute spline adapter (see figure 17) may achieve an adequate low wear, high reliability coupling capable of maximum torque transmission with minimum manufacturing cost.



TOOTH ARC LENGTH = 0.065
(CIRCULAR TOOTH)

TOOTH HEIGHT = 0.100
(FLAT TOOTH)

METRIC CONVERSION
1 inch = 25.4 mm

Flat tooth has approximately 50 percent more surface area per unit spline length (effective contact area) than the circular spline.

Figure 16
Comparison of the Flat Tooth and Circular Spline for the 5/8 Inch Pitch Diameter Plastic and Steel Torque Coupling

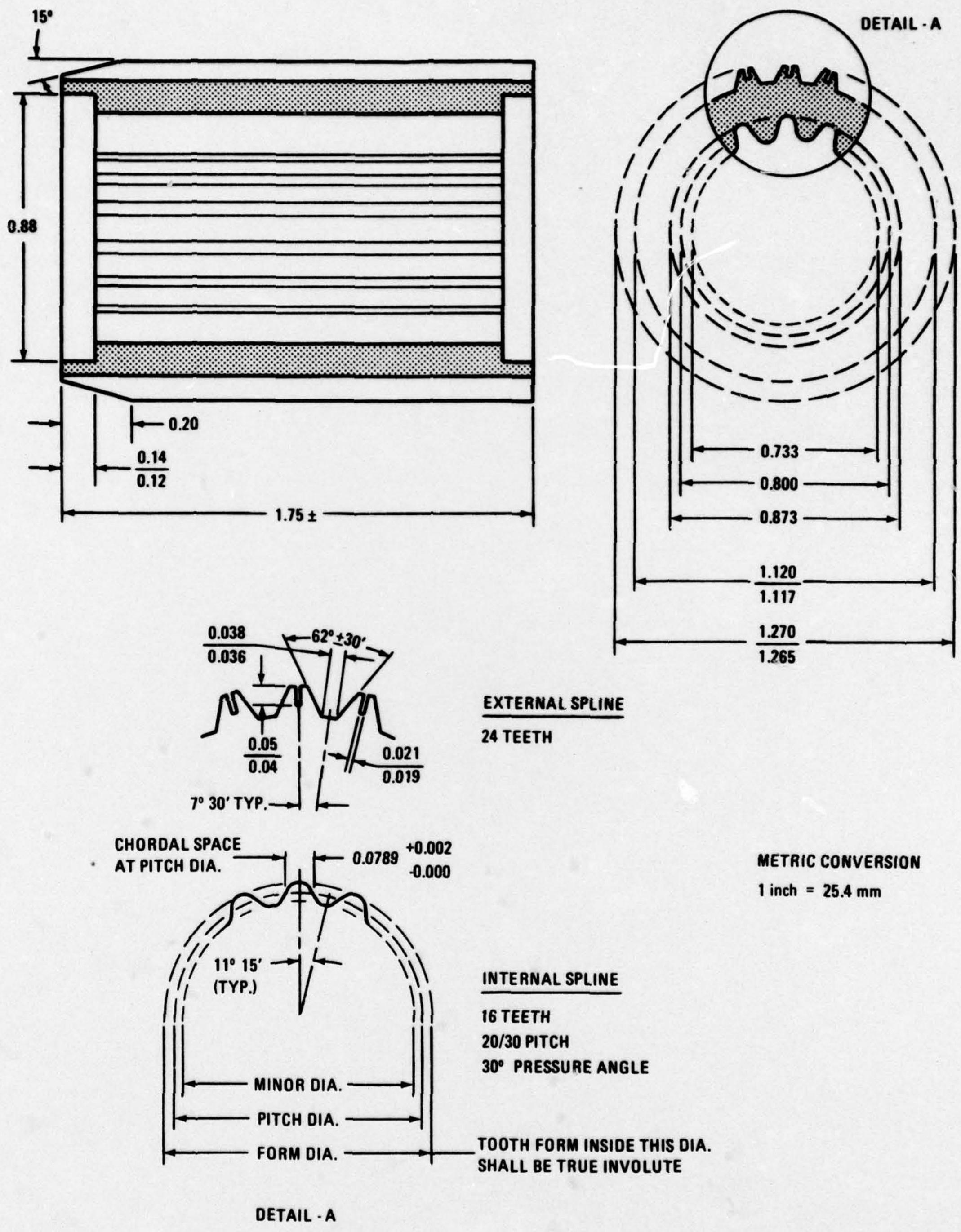


Figure 17
Proposed Polyimide Plastic Involute Spline Adapter

CONCLUSIONS

26. In excess of 20,000 hours of flight testing on four aircraft types, plus extensive laboratory testing, have demonstrated the value of the circular spline coupling. Wear and coupling failure are essentially eliminated as a cause of accessory power system low reliability when this coupling technique is used.

27. Significant savings in maintenance man-power and resources are possible by using the high-strength plastic adapter to reclaim otherwise serviceable engine driven gearboxes at the organizational maintenance level.

28. The small 5/8 inch (16 mm) pump, starter, and emergency generator couplings will be similarly improved by the six toothed steel shaft and polyimide plastic spline adapter described herein.

29. Further design improvements and economy may be afforded by the polyimide plastic involute spline adapter proposed as a replacement for the circular spline coupling.

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